Final Engineering Report

RESEARCH ON THIN MAGNETIC FILM LOGIC DEVICES

Prepared for:

JET PROPULSION LABORATORIES
4800 OAK GROVE AVENUE
PASADENA, CALIFORNIA

P.O. N-30004 UNDER
CONTRACT NASw-6

By: M. W. Green

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ABSTRACT

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An attempt was made to demonstrate the feasibility of an all-magnetic-logic system consisting of thin ferromagnetic films interconnected by passive thin-film coupling structures. A theoretical analysis of the dynamic behavior of two coupled magnetic-film elements is presented which tends to support the feasibility of the system, but only if extremely good coherent rotation of magnetization can be obtained, and if driving conditions can be very carefully controlled. Equipment was designed and constructed for the purpose of fabricating multi-layer evaporated structures of the desired type. A novel feature of this apparatus is a means for measuring film thicknesses that employs several photocells located inside the vacuum chamber. Numerous multi-layer devices with two magnetic elements were then produced. High-speed pulse measurements of several types were carried out to determine the properties of the magnetic films and coupling circuitry. Flux transfer between two elements was investigated with interesting but inconclusive results. However, the difficulty in producing magnetic films of the desired high quality, the need for precise control of drivers, and the probable difficulty in providing logical fan-out, make this approach appear less attractive than some of the competing high speed logic schemes.

Auth. Author

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I INTRODUCTION

During the last several years, the properties of thin ferromagnetic films have become the subject of considerable scientific attention. From a theoretical standpoint thin films offer a unique opportunity to study certain aspects of magnetic behavior under relatively idealized conditions. For example, films can be prepared that consist of a single magnetic domain so that measurements can be secured without the complication of domain-wall motions. Alternatively, interesting special types of domain structure may be produced and observed with relative ease under static or dynamic conditions. Generally speaking, the effects of various structural anisotropies, stains etc. are more easily studied and understood in thin-film specimens where domain configurations are essentially two-dimensional. Persistent experimental and theoretical work in such areas by a number of different laboratories has contributed a great deal to basic knowledge of magnetic processes. Practical consequences of this work have been the invention of several new magnetic devices with interesting applications in the digital computer field.

From a device standpoint the possibility of using single-domain ferromagnetic films with uniaxial anisotropy has proved particularly intriguing. These films, first studied by Blois,[1] can be produced by vacuum vapor-deposition in a homogeneous magnetic field. Typical film specimens prepared in this manner showed two stable states with oppositely oriented remanent magnetization. Furthermore, switching between the two states could be accomplished by coherent rotation of the magnetization direction rather than by domain-wall motion. These properties provided the ability to store binary information and to switch very rapidly between states. The latter high switching speeds were expected (and found) because the switching process involved no domain-wall propagation and no eddy-current damping of any significance.[2-5] Subsequently, use of thin permalloy film patches for high-speed memory elements in computers was successfully attempted by Smith and Raffel and is now a relatively standard technique.

About three years ago we became interested in the possibility of using thin permalloy films in magnetic logic systems. Several plausible schemes were proposed at about this time (by Engelbart,[6] Proebster,[7] Lo,* and possibly others) to make use of coherent rotation of magnetization for logical manipulations and storage in networks of coupled thin-film elements. The expected advantages to be obtained over similar all-magnetic logic networks using ferrite elements were: much higher speed and better temperature immunity. Under sponsorship of the Air Force we made a preliminary experimental and theoretical study of the feasibility of thin-film logic devices employing the guided fall-back mode of information transfer.[8] This study included a series of low-speed pulse measurements on thin permalloy film samples which provided the quantitative data necessary to develop a rather extensive theoretical analysis of the proposed flux-transfer mechanism and its associated coupling structures. From this work we concluded that the analyzed logic system should have a good chance of practical implementation. No actual logic devices were constructed, however, because of the lack of equipment to produce the multi-layer evaporated coupling structures required.

In August of 1960 Jet Propulsion Laboratories provided us with the necessary support to continue thin-film-logic investigations with realistic device configurations. It was agreed that we would direct the major effort toward realizing the basic system requirement of lossless positive transfer of information between two thin-film elements.

* Personal communication.

II PROGRAM DESCRIPTION

The principal objective of this research program was to investigate the practical feasibility of magnetic logic networks employing thin permalloy films connected by passive-coupling loop structures. System concepts have been described in Refs. 6 and 8. Very briefly, the proposed logic networks would make use of multi-phase clock drivers to produce unidirectional propagation of information, linear-input (majority) logic between stages, and the guided fall-back mode of flux transfer between successive film elements. The latter method of information transfer will be discussed in Sec. III.

At the outset it was realized that the proposed logic system would stand or fall on the ability to transfer flux between successive film elements without accompanying loss. We felt that this capability could be satisfactorily demonstrated with devices containing only two thin-film elements. We consequently confined our experimental efforts to symmetrical two-element devices furnished with a single common coupling-loop structure. Some specific program objectives as expressed in our original proposal are as follows:

(1) Explore the feasibility of logic realization with thin films according to the procedures mentioned above, with particular emphasis on experimental reduction to practice of a simple positive transfer logic element.

(2) Attempt to demonstrate transfer of information between thin-film elements at speeds of operation substantially in excess of those presently obtained with ferrite devices.

(3) To analyze and understand the reasons for failure if the postulated devices do not prove to be feasible.

Program effort toward these goals may be divided roughly into three areas: (1) A theoretical phase in which the proposed switching experiment was re-examined in order to have some definite prior expectations as to the outcome of subsequent experimental measurements; (2) A design and construction phase in which equipment for fabricating thin-film devices was conceived, built and checked-out. (3) An experimental measurements phase in which a series of thin film devices were produced and investigated under pulsed field conditions. Although some portions of the work were carried out concurrently it will be convenient to report on these phases separately in the following three sections.

III COUPLED THIN-FILM ELEMENTS

A. THE FLUX-TRANSFER PROCESS

Visualize a magnetic logic system in which information resides in the remanent magnetic condition of individual "spots" of thin permalloy film. That is, each film element possesses a well defined uniaxial anisotropy, and the "one" and "zero" states correspond to single-domain conditions with oppositely oriented magnetization vectors. Film elements are connected together by passive transmission-line circuitry. At appropriate clock-times some sub-set of elements will be required to transmit a logical combination of its remanent flux states to a set of receiving film elements. The receiving elements will in turn become transmitting elements during a subsequent clock phase so that information will be propagated through the network. If the coupling circuitry is indeed passive it will be necessary to provide some mechanism for re-establishing a standard reference value of remanent flux in receiving elements even though transmitted flux linkages are lost in dissipative coupling circuitry. Thus, a flux-gain requirement during transfer of information is implied.

The means we have hypothesized to secure this required flux gain will be referred to as the guided fall-back mode of operation. Reliable operation of this type of flux-transfer mechanism between two similar thin-film elements would virtually guarantee the realizibility of more complex logic networks employing the same principle. Most of our project effort was directed toward establishment of the guided fall-back mode as an experimental fact. To this end, we devised the basic experiment depicted in Fig. 1.

We planned to fabricate a series of thin magnetic-film devices much like that shown schematically at the top of the figure. The circular discs are patches of 80% to 20% nickel-iron permalloy (composition chosen for zero magnetostrictive coefficient). The coupling loop or "strap" is a very thin transmission line consisting of evaporated copper layers separated by silicon-monoxide insulation. One of the completed devices is shown in Fig. 2, with the drive and bias winding removed so that the magnetic spots are more easily seen.

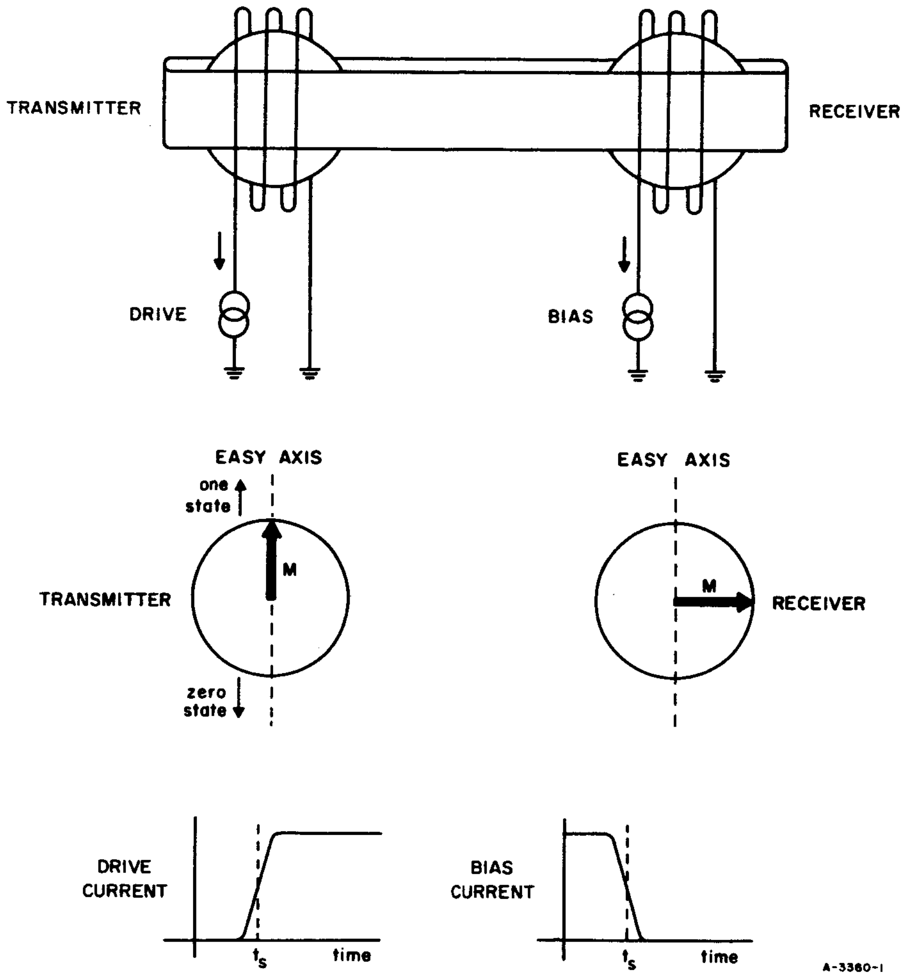

FIG. 1 SCHEMATIC ILLUSTRATION OF A PAIR OF COUPLED THIN-MAGNETIC-FILM ELEMENTS IN THE READY-TO-TRANSMIT CONDITION

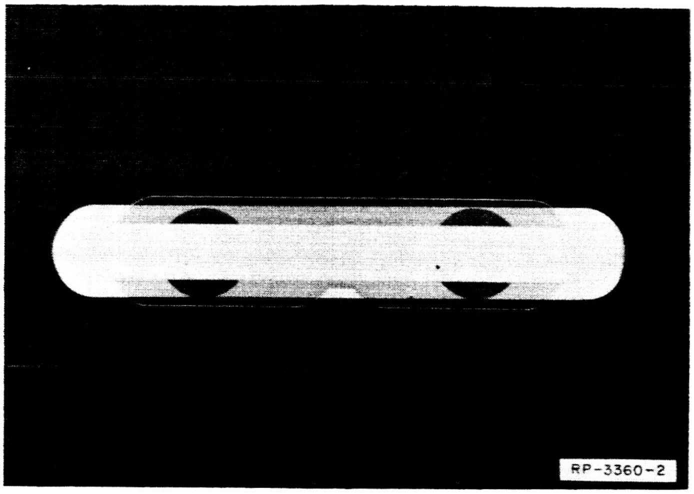

FIG. 2 TWO-ELEMENT THIN-MAGNETIC-FILM REGISTER

The guided fall-back mode of information transfer works as follows: Initially the transmitter element is in a "resting" state with all of its magnetization oriented along one of the two easy-axis directions. A steady bias current holds the magnetization of the receiver element in the transverse direction at right angles to the easy axis of the receiver (see Fig. 1). To effect the transfer, a drive current is suddenly applied to the transmitter element (through the winding shown) which rapidly rotates the magnetization of the transmitter element toward the transverse axis. At the same time, t_s, that the transmitter element is switching, the bias current is removed from the receiver element. The switching voltage produced by the transmitter element sends a current through the coupling loop which produces an H field at the receiver element directed toward the same easy-axis direction as originally occupied by the transmitter magnetization. This "guiding field" tends to steer the receiver magnetization toward the easy-axis direction by a coherent rotation of M. Once the motion of M toward an easy-axis direction is established, internal torque produced by the "built in" uni-axial anisotropy restores M to the minimum energy position. At the conclusion of a successful transfer all of the receiver magnetization would be found directed along the easy axis while the transmitter element would be strongly held in the transverse direction. The roles of transmitter and receiver are consequently reversed after a transfer. The receiver is ready to transmit and the transmitter is ready to receive.

During such a transfer, there is a very delicate balance of forces acting on the receiver magnetization M. At some intermediate point in the switching process let the angle the receiver M makes with the easy axis be θ. The several forces which influence the position and motion of M can be separately identified as follows: The bias field H_t produces a torque per unit volume of magnetic material

$$T_{bias} = H_t M \cos\theta \qquad \text{newton/meter}^2 \tag{1}$$

tending to rotate M toward the transverse axis. The switching field H_s provided by the transmitter element causes an opposing torque

$$T_{guide} = H_s M \sin\theta \qquad \text{newton/meter}^2 \tag{2}$$

tending to rotate M toward the easy axis direction.

In addition to these externally applied torques, the uniaxial anisotropy of the film element produces a third torque tending to return M to either easy axis position. This is the torque we must depend upon to secure the required flux gain during transfer. The anisotropy of the film corresponds to an angularly dependent potential energy term of the form

$$W = K \sin^2\theta \qquad \text{newton/meter}^2 \tag{3}$$

where K is often called the anisotropy constant and W is the internal energy per unit volume associated with a given magnetization direction. Coherent rotation, implying a constant absolute magnitude of M, is assumed. The torque due to anisotropy can be found by differentiating Eq. (3) with respect to θ. This leads to

$$T_{anisotropy} = H_k M \sin\theta \cos\theta \qquad \text{newton/meter}^2 \tag{4}$$

where $H_k = 2K/M$ is a characteristic transverse coercive field for the film element. Throughout this discussion the dimensions of M are assumed identical to B, namely volt seconds/meter^2.

Finally, there are several additional dynamic forces that act only when M is in motion. Gyroscopic reactions, viscous damping, and eddy currents induced in the film and in neighboring conductors all produce torques that tend to oppose the motion of M. Each of these "drag" forces contributes to a practical limitation on maximum switching speed of the receiver element. At switching speeds of interest to us, viscous damping and eddy current effects predominate. These reactions torques may be lumped together as

$$T_{\mathrm{drag}} = kM \frac{d\theta}{dt} \qquad \text{newton/meter}^2 \qquad (5)$$

where k is a numerically small constant ($\approx 10^{-7}$ coulomb/meter) that can be estimated from gyromagnetic resonance experiments and detailed calculations of expected eddy-current damping effects.[8]

B. LOW-SPEED RECEIVER DYNAMICS

If the magnetization of the receiver element is coherently rotated by applied H fields that are slowly varying with time, drag torques proportional to the angular velocity of M may be ignored. It is a good approximation, then, to assume that M is in a static equilibrium state at each moment of time. The instantaneous position of M may therefore be found by setting

$$T_{\mathrm{bias}} + T_{\mathrm{guide}} + T_{\mathrm{anisotropy}} = 0 \quad . \qquad (6)$$

A convenient way to present the solution of this torque equilibrium equation is shown in Fig. 3. The abscissa measures the transverse bias or "holding" field as a multiple of H_k. The ordinate is the angle that M assumes for a given combination of applied bias and switching fields measured from a reference direction along the easy axis of the film. The θ scale has been inverted so that lines drawn from the origin to points on a curve take the same general direction as M in the film. The three curves are for fixed values of H_s equal to 1 percent, 5 percent, and 10 percent of H_k respectively. Each curve actually represents a cross section of a three-dimensional surface which would display the equilibrium position of M for any given combination of bias and switching fields whose resultant lies in the first quadrant.

The cross-hatched area near the origin of Fig. 3 indicates a region that should be avoided when attempting a guided fall-back of M. In this region M would be required to maintain an equilibrium position very near

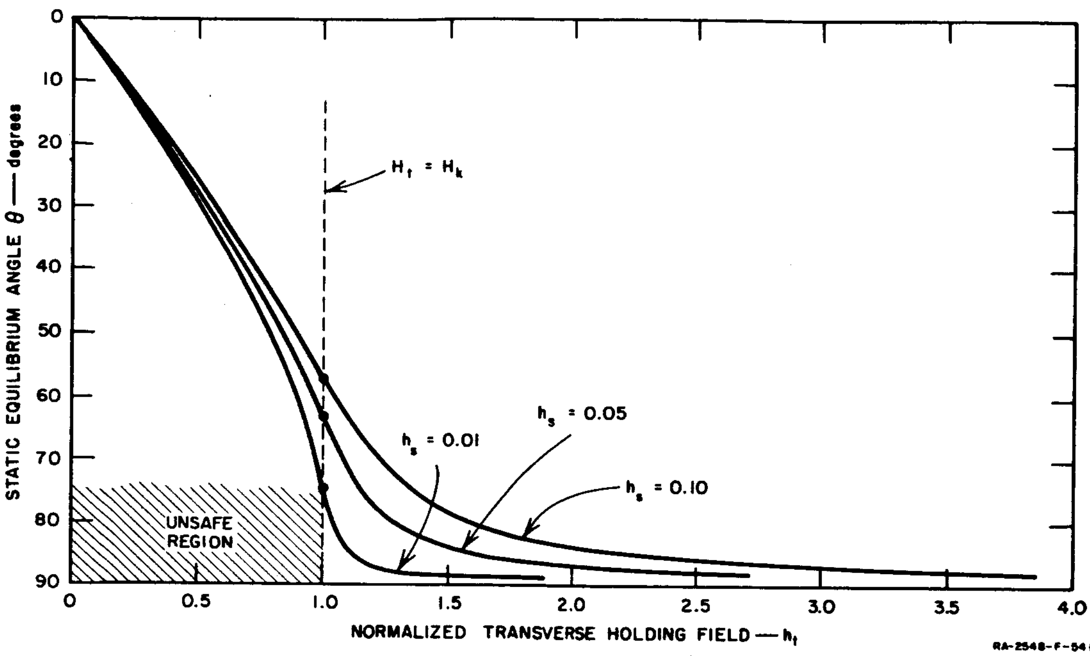

FIG. 3 STATIC EQUILIBRIUM ANGLE AS A FUNCTION OF TRANSVERSE BIAS FIELD FOR VARIOUS VALUES OF SWITCHING FIELD

the transverse axis under conditions where total applied fields amounted to less than H_k. We know from numerous low-speed switching measurements that a failure of the coherent rotation mechanism occurs under these circumstances. As long as external fields are in excess of H_k the film specimen will retain the character of a single saturated domain whatever the orientation of M. If, however, external fields are reduced in such a way that M finds itself very near the transverse axis a "break-up" into many disorganized domains is likely to occur. When this happens the torque due to anisotropy fails and the film magnetization does not return to the easy axis. We do not know how long it takes for this type of "break-up" to occur. Possibly a rapid transition through part of the "unsafe" cross-hatched region might be achieved before domain structures had sufficient time to nucleate and grow. From a practical standpoint the "unsafe" region of a very good film specimen will be above angles of about 77°. Thus, referring to Fig. 3 the "unsafe" region may be completely avoided if switching fields H_s of only 2 or 3 percent of H_k can be maintained while the bias field collapses.

C. DYNAMICS OF A COUPLED FILM PAIR

When two thin-film elements are connected together by a dissipative coupling loop and the attempt is made to transfer flux from one to the other by a guided fall-back switching process, the dynamical situation becomes quite complex. Not only are all the magnetization changes non-linear functions of the applied fields, but interaction between film elements is also non-linear, speed-dependent and lossy. Under these circumstances it is very difficult to develop a trustworthy heuristic picture of what actually transpires during a flux transfer. Even the customarily useful "rule of thumb" notions which rely on conservation of flux and current are nearly worthless in this case since flux losses in the coupling loop may vary by orders of magnitude, depending upon the switching regime chosen.

In order to have a better understanding of what to expect in actual experimental conditions we decided to set up and solve the dynamical equations for a pair of coupled elements. The mathematical model selected was sufficiently realistic to display most of the important features of coupled film behavior. We were particularly interested to see whether drive and bias conditions could be found such that the "unsafe" region of receiver operation indicated in Fig. 3 would be avoided. We also wished to determine how sensitive the switching conditions would be to timing of the drive and bias waveforms. Finally, we hoped that solutions of the dynamical equation would indicate whether fan-out to more than one receiver element should be feasible.

The nomenclature and sign conventions used in constructing the dynamical equations are illustrated in Fig. 4. H_t^t and H_t^r are the external fields in the transverse direction applied to the transmitter and receiver respectively by the drive and bias windings (not shown in the figure). H_s^t and H_s^r are the field strengths in the easy-axis direction at the transmitter and receiver produced by flow of current in the coupling loop. As the transmitter magnetization rotates clockwise toward the transverse axis the receiver magnetization rotates counterclockwise toward the easy axis. The polarities of both transmitter- and receiver-induced voltages are consequently positive on the upper conductor of the coupling loop. The direction of coupling-loop current is considered to be positive when flowing from left to right in the upper strap of the loop. With this convention the easy-axis fields H_s^t and H_s^r are both directed upward on

Fig. 4 for positive loop current I_s. As will be seen later, the direction of I_s may actually reverse during a typical switching cycle so that H_s^t and H_s^r will simultaneously change direction.

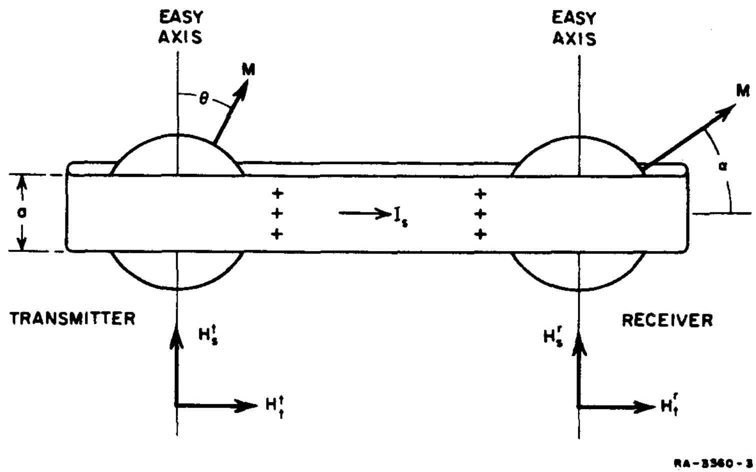

FIG. 4 NOMENCLATURE EMPLOYED IN DYNAMIC SWITCHING STUDIES

An equivalent circuit for the passive lossy coupling loop is depicted in Fig. 5. The voltages induced in the loop by changes in transmitter and receiver magnetization direction are indicated by the two generators e_t and e_r. The voltage e_t drives a switching current I_s^t into the coupling loop, but only a portion of the current I_t^r is effective in guiding the receiver element. The coupling loop actually should be treated as a section of strip transmission line; however, the lumped circuit representation of Fig. 5 is quite adequate for the very short lengths of strip line we will be considering. Indeed, it can be shown that for moderate-to-fast switching speeds (1 to 20 nanoseconds) coupling loop reactances are considerably less important than resistive losses in a typical flux transfer. In particular, if the dielectric material chosen for insulation of the strip-line conductors has the proper amount of high-frequency conductivity the coupling loop can appear resistive at all frequencies of interest. Consequently it is a reasonably good approximation to assume that the coupling-loop equivalent circuit shown in Fig. 5 has only resistive elements. We have made this assumption in the following analysis. A more complete discussion of coupling-loop parameters may be found in Ref. 8, Sec. IV.

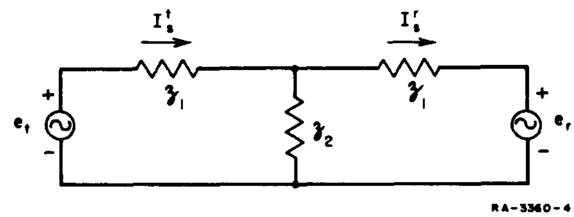

FIG. 5 EQUIVALENT CIRCUIT FOR THIN STRIP-TRANSMISSION-LINE COUPLING LOOP

With the aid of the equivalent circuit, the instantaneous currents flowing in the transmitter and receiver ends of the coupling loop may be calculated. Superscripts again differentiate between transmitter and receiver quantities.

$$\begin{aligned} I_s^t &= g_1 e_t - g_2 e_r \quad \text{amperes} \\ I_s^r &= g_2 e_t - g_1 e_r \quad \text{amperes.} \end{aligned} \tag{7}$$

The conductances g_1 and g_2 depend upon the characteristic impedance and attenuation of the coupling loop chosen. Numerical values for g_1 and g_2 may therefore be calculated from an assumed loop geometry or measured in a case of practical interest. The voltages e_t and e_r produced by coherent rotation of transmitter and receiver magnetization vectors are given by

$$e_t = \phi \sin \theta \frac{d\theta}{dt} \quad \text{volts}$$

$$e_r = \phi \cos \alpha \frac{d\alpha}{dt} \quad \text{volts} \quad . \tag{8}$$

These voltages are obtained by time differentiation of the flux linkages enclosed by the coupling loop at the transmitter and receiver elements respectively. ϕ, the total remanent magnetic flux of a film element, is assumed to be the same for each film, namely M times the film cross-sectional area.

The easy-axis switching fields due to flow of coupling loop current may now be expressed for both film elements with the aid of Eqs. (7) and (8). They are:

$$H_s^t = a^{-1}g_1 \phi \sin \theta \dot{\theta} - a^{-1}g_2 \phi \cos \alpha\dot{\alpha} \quad \text{amp/meter}$$

$$H_s^r = a^{-1}g_2 \phi \sin \theta \dot{\theta} - a^{-1}g_1 \phi \cos \alpha\dot{\alpha} \quad \text{amp/meter.} \tag{9}$$

Here and subsequently a is the width of the coupling-loop strap in meters, and dotted quantities are time derivitives.

H_s^t and H_s^r are the *only* forces that act on the film elements because of the presence of the coupling loop. The forces *not* associated with coupling-loop action and reaction are applied drive and bias fields, the anisotropy torques, and the damping torques. The summation of all of these applied and reaction forces completely determines the dynamic behavior of the two coupled elements. Accordingly we finally obtain the following set of differential equations representing the motion of transmitter and receiver magnetization vectors under arbitrary drive and bias excitations:

$$MH_t^t \cos \theta - MH_s^t \sin \theta - Mk\dot{\theta} = 2K \sin \theta \cos \theta$$

$$MH_t^r \sin \alpha - MH_s^r \cos \alpha + Mk\dot{\alpha} = 2K \sin \alpha \cos \alpha \tag{10}$$

where H_s^t and H_s^r have the form stated in Eq. (9), and H_t^t and H_t^r represent drive and bias fields. When these quantities are inserted in Eq. (10) and some of the constants are combined, the dynamic equations reduce to:

$$I_t \cos\theta - q_1 \sin^2\theta\,\dot{\theta} + q_2 \sin\theta \cos\alpha\dot{\alpha} - q_3\dot{\theta} = I_k \sin\theta\cos\theta$$

$$I_r \sin\theta + q_1 \cos^2\alpha\,\dot{\alpha} - q_2 \sin\theta\cos\alpha\dot{\theta} + q_3\dot{\alpha} = I_k \sin\alpha\cos\alpha \quad . \tag{11}$$

here I_t and I_r are the transmitter and receiver drive and bias currents, and I_k is a constant current equivalent to a field of H_k. The constants q_1, q_2, and q_3 have the dimensions of charge, and are equal to $g_1\phi$, $g_2\phi$ and ak respectively.

The simultaneous equation, Eq. (11), furnished a complete description of transmitter and receiver conditions during switching, but it is very difficult to obtain any closed-form solutions of practical interest. Instead of attempting an analytic treatment we programmed the equations for solution on the Burroughs 220 digital computer. The program was arranged so that separate cases of interest could be solved by assigning nine parameters to a standard subroutine. A number of solutions were obtained in which we sought to optimize the timing relationship between drive and bias excitations. The effects of coupling-loop impedance and loss were also investigated.

The solutions obtained showed a number of interesting features (some of them unexpected) that have a direct bearing on best-case device performance. Figure 6 shows one machine solution which is very close to optimum with respect to timing of drive and bias waveforms. In this run, coupling-loop iterative impedance was assumed to be 0.75 ohm with an attenuation between film elements of 0.8. Both films were assigned a remanent flux of 10^{-9} weber corresponding to dimensions of one centimeter in diameter and approximately 1000 Å thickness. The drive and bias fields are illustrated in the upper left-hand corner of Fig. 6. Drive current rises linearly from zero to a value sufficient to apply an H_t field of $3H_k$ to the transmitter after an interval of 20 nanoseconds. The bias current at the receiver is meanwhile decaying toward zero in such a way that the receiver bias becomes less than H_k one nanosecond *before* transmitter drive reaches H_k, which in this example was assumed to be 2.5 oersteds.

Figure 6 is a composite graph of the transmitter and receiver voltage waveforms and the angular positions of their respective magnetization vectors θ and α. Timing of the drive and bias excitations is known to be nearly optimum in the case illustrated because the transmitter and

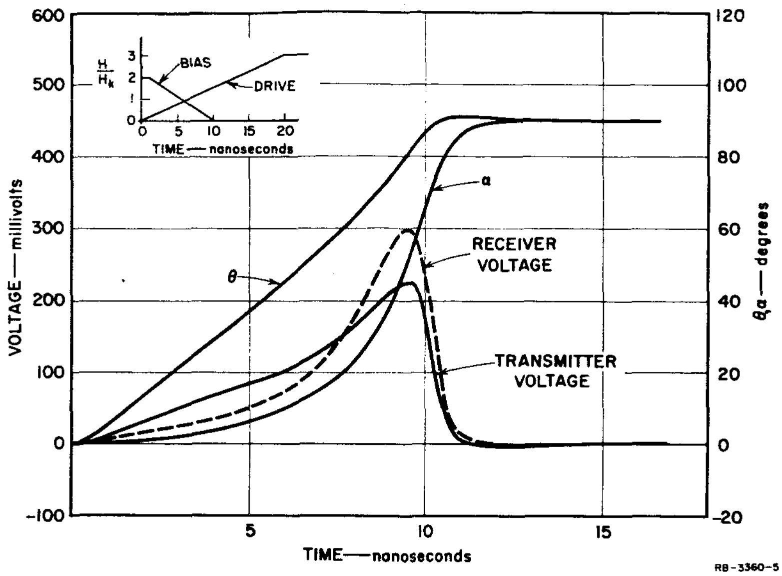

FIG. 6 CALCULATED TRANSMITTER AND RECEIVER VOLTAGES AND ANGLES IN A WELL SYNCHRONIZED SWITCHING REGIME

receiver voltages are very nearly in phase with each other. Other switching regimes show a pronounced lag of receiver voltage with respect to transmitter voltage. Some particularly important aspects of the switching cycle shown in Fig. 6 are noted below:

(1) At 60° when only one-half of the available transmitter flux has been switched, the receiver voltage becomes greater than the transmitter voltage. This means that current in the coupling loop reverses and the transmitter is no longer effective in steering the receiver element. In fact, the receiver continuing to switch under the influence of its anisotropy torque pumps energy back into the transmitter in such a way that the transmitter is aided in completing its switching and actually overshoots the transverse axis.

(2) During the early part of the switching cycle the total flux switched at the receiver is only about one-half of the transmitter flux of the switch even though the attenuation of the coupling loop is rather small (0.8).

(3) At the moment when the total field applied to the receiver element becomes less than H_k, the receiver magnetization has an angle α of only 10° away from the transverse axis. This means that M is actually transversing a corner of the "unsafe" region described with reference to Fig. 3. Because θ is increasing rapidly at this time and actually reaches a value

of 20° less than two nanoseconds later it is probable that no "break-up" would occur in this case. Nevertheless, it appears to be difficult (with some sets of assumed coupling-loop and film parameters, impossible) to achieve switching regimes which completely avoid receiver field conditions that would lead to domain formation under static conditions.

Another solution obtained for a different set of drive conditions is shown in Fig. 7. In this case drive was applied more rapidly to obtain a larger transmitter voltage. Receiver bias was relaxed somewhat later in the switching cycle in order to give the transmitter voltage more time to act on the receiver magnetization. Notice that the receiver voltage lags the transmitter voltage in a very pronounced way in this example. Receiver voltage, reaching a maximum *after* the transmitter has completed switching, causes a distinct overshoot of transmitter magnetization beyond the transverse axis. Once again, however, the receiver angle reaches a value of about 10° at the time receiver applied field conditions are critical.

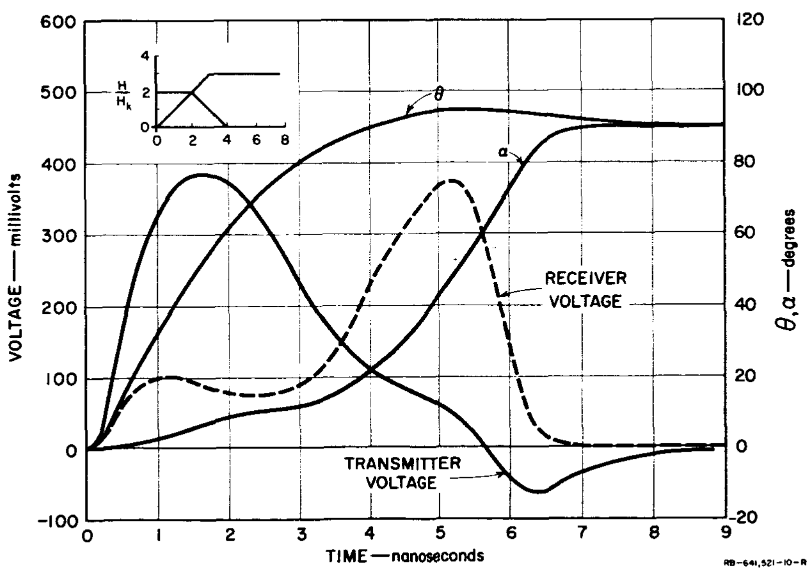

FIG. 7 CALCULATED TRANSMITTER AND RECEIVER VOLTAGES AND ANGLES IN A DELAYED SWITCHING REGIME

From a study of a number of special cases of the above types we were able to form the following conclusions:

(1) Transmitter-receiver interaction in the guided fall-back mode is a very sensitive function of the magnitude and relative timing of drive and bias excitations. This fact would very likely have unpleasant consequences in logic systems containing many elements where maintenance of stable jitter-free clock sources would be absolutely necessary.

(2) Low coercive-field films with good rotational behavior appear to be essential to satisfactory guided fall-back operation, since no switching modes were found that did not involve receiver conditions that are known to be marginal. In particular, receiver angle α is always small when receiver bias initially becomes small. Low coercive field has about the same effect as low coupling-loop impedance in producing a more favorable ratio of flux switched to flux lost.

(3) Direct fan-out from one transmitter element to two or more *parallel*-connected receiver elements appears to be possible although films would have to be very "good" for this purpose. The reason is that a fan-out of two implies a minimum effective coupling loop attenuation of 0.5 with respect to each receiver guiding current. Fan-out from one transmitter to two or more *series*-connected receiver elements seems to be even more difficult because transmitted flux must divide between receiver elements.

IV FILM-FABRICATION APPARATUS AND TECHNIQUES

A. FABRICATION METHODS

During the preliminary planning stages of the device fabrication program we had hoped that it might prove feasible to "assemble" the required coupled film pairs rather than produce them as an integrated unit. The methods we considered would have involved several steps. First, a rigid substrate with a conductive coating would have been prepared by evaporating copper or aluminum on glass. In a second evaporation process involving a different vacuum chamber, two permalloy film spots would have been deposited on the conductive substrate. Subsequently a layer of organic or plastic insulation would have been applied by spraying or dipping to an area covering the film spots and a rectangular region between them. Finally, an upper strap made from thin metal foil would have completed the loop around the film spots by means of connections made to ends of the conductive substrate.

This general type of construction sounded comparatively simple and straightforward and it had the advantage that available equipment might be used to deposit the permalloy films. On the other hand, an important danger existed that one or more of the untried steps in the proposed fabrication process would fail to work out in practice. This eventuality would have left us in the awkward position of being committed to an impractical scheme when project effort had already reached an advanced phase. The alternative was to plan for the construction of devices by multiple vacuum evaporations in a piece of equipment especially designed for that purpose. This would have involved the construction of a rather elaborate piece of vacuum apparatus, but greater flexibility and assurance in fabrication techniques would have been secured.

After considerable thought we decided to abandon "assembly" types of film device construction in favor of the integrated approach involving multiple evaporation. There were several reasons for making this decision and it seems worthwhile to list a few of these in order to indicate the nature of the expected difficulties:

(1) We were afraid to proceed under the assumption that permalloy films would behave satisfactorily when deposited on a bare metal substrate. Assuming that insulation *might* be required between film spots and substrate, such insulation would have to be very smooth and sufficiently inert to survive the 300°C substrate temperature required for evaporation of permalloy. This implied that a third vacuum evaporation of something like silicon monoxide would be required in any event, or that some other technique such as selective anodization of thin aluminum films would have to be developed.

(2) Preparation of suitable insulating layers to be applied outside the vacuum chamber might prove to be difficult. Some preliminary experiments in this direction were discouraging. It was hard to achieve very thin layers that were reasonably free from imperfections. Also, some chemical activity between the insulation and the magnetic material was noted.

(3) Closure of the coupling loop by a separate metal foil strap presents a problem of making end connections to the substrate conductor. This could prove very troublesome because the closure strap must be a very thin conductor to avoid eddy-current effects and it would therefore be very delicate. Evaporation of this portion of the coupling loop would be easy, but again the underlying insulating material would have to be relatively inert.

(4) One can usually expect a high rejection rate when multistep processes require much intermediate handling and exposure to environmental conditions that are not well controlled. Such problems can be avoided if all fabrication steps take place in the same evacuated chamber at approximately the same time.

B. TWO-ELEMENT REGISTER DESIGN

Having decided on the integrated structure as the most promising method of producing the desired coupled film device we proceeded to design the experimental two element register shown in Fig. 8. The substrate is a one-by-three-inch microscope slide. Film spots are about one cm in diameter. Other dimensions are approximately to scale. The unit requires six separate evaporations if magnetic elements are deposited one at a time. The thickness of the various layers indicated in Fig. 8 are approximate and subject to experimentation. Good rotational behavior has

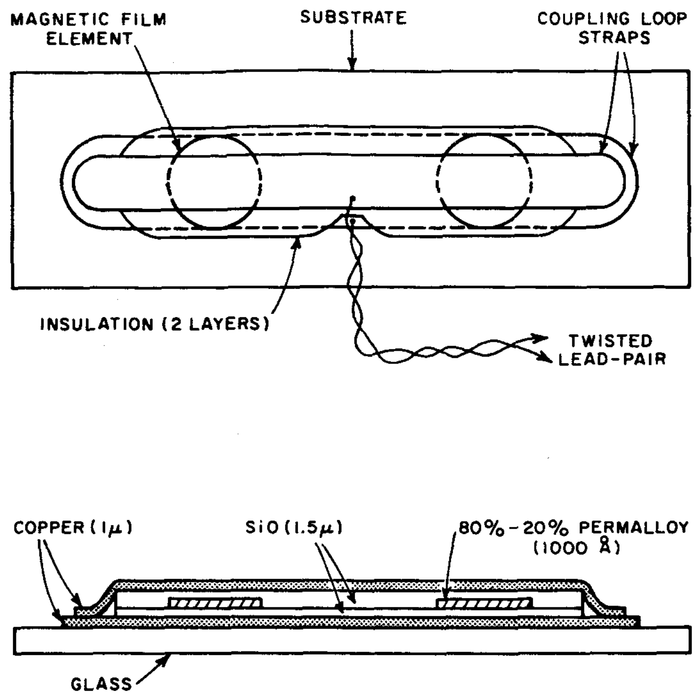

FIG. 8 PRELIMINARY DESIGN FOR A TWO-ELEMENT THIN-MAGNETIC-FILM REGISTER

been observed in our own experiments with permalloy elements about 1000Å thick. The thickness of copper and silicon monoxide were selected to produce a strip transmission line with an iterative impedance of about $1/3$ ohm. The switching behavior of a device made according to these specifications should consequently be similar to the theoretical model discussed with reference to Fig. 6. A picture of a completed two-element register has already been illustrated in Fig. 2.

C. VACUUM VAPOR DEPOSITION EQUIPMENT

The apparatus designed and built for the purpose of fabricating the magnetic-film structure is shown in Figs. 9 and 10. The dimensions and general mechanical details are designed to be compatible with a standard Vecco laboratory vacuum system having an 18-inch bell jar. To describe this machine we can begin at the bottom and work our way to the top. A heavy base plate supported on three legs is fitted with four permanently affixed sets of terminals for four evaporation stations. Surrounding and extending upward from each evaporator station is a "chimney" consisting

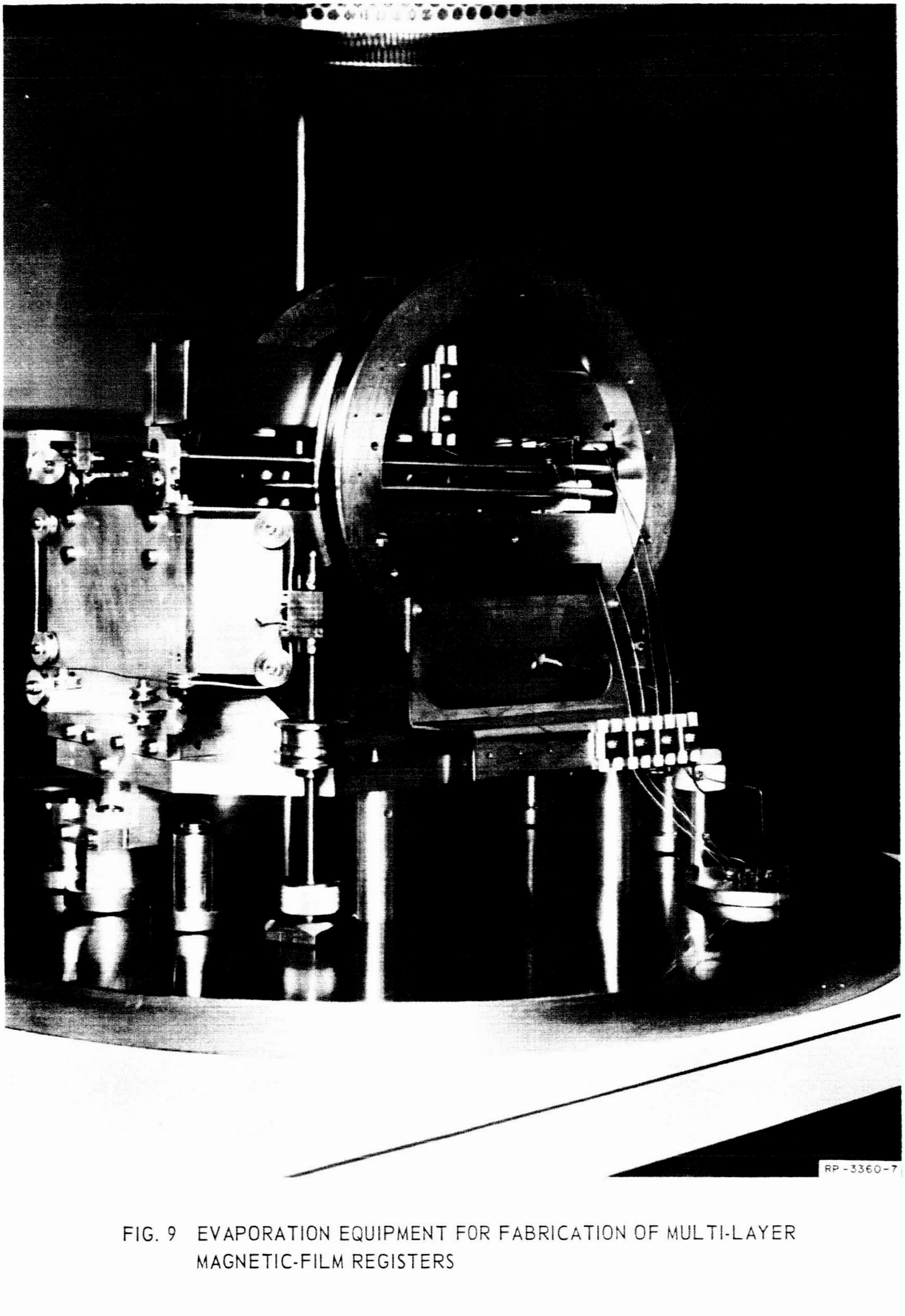

FIG. 9 EVAPORATION EQUIPMENT FOR FABRICATION OF MULTI-LAYER MAGNETIC-FILM REGISTERS

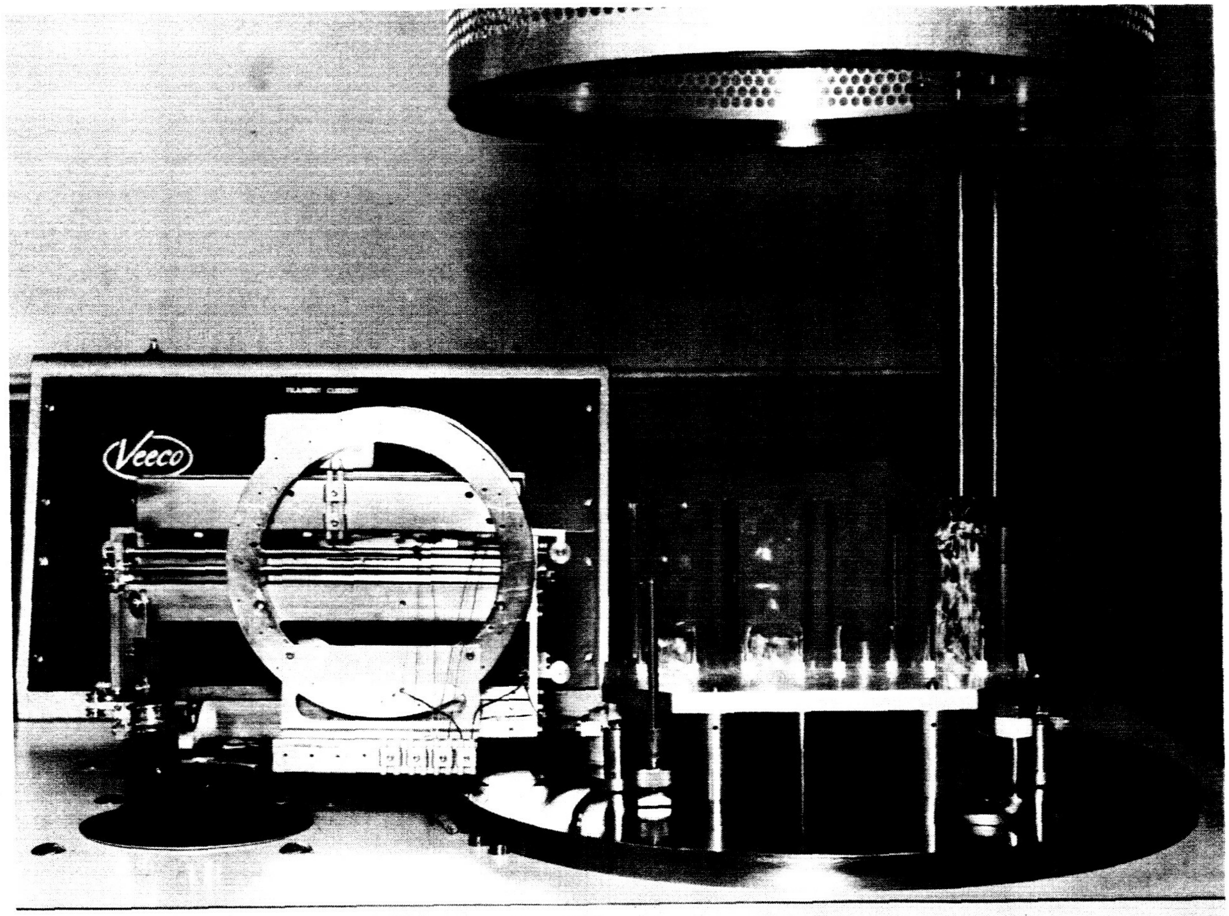

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FIG. 10 EVAPORATION EQUIPMENT DISASSEMBLED TO SHOW EVAPORATOR CHIMNEYS

of a flattened pyrex glass tube for the purpose of confining evaporated materials to easily cleaned removable surfaces. Above the evaporator "chimneys" are a set of fixtures which hold stainless steel masks for the purpose of defining the areas through which evaporated materials can pass. Just over the mask array is a movable carriage that supports the glass substrate on which the thin-film register is deposited. This carriage can be transported from one evaporator station to another by manipulating one external control cable that enters through the base plate of the vacuum chamber. This control cable has two degrees of freedom. A translational motion causes the substrate carriage to be lifted vertically away from the mask array. A subsequent rotational motion of the cable moves the carriage to a new evaporator location. A final translational motion of the cable drops the carriage onto the new mask location. This type of mechanical motion eliminates any scraping or abrasion of the substrate by mask structures and allows very precise indexing of substrate location by means of a number of indexing slots into which the carriage may be dropped.

Above one of the evaporator stations (the one normally used for evaporation of permalloy) is a small box the same size as the microscope slide substrate containing a resistance wire heater. By radiation, this heater can raise the substrate temperature to about 300°C, the desired condition for producing magnetic films with good uniaxial anisotropy. The heater was designed to have a negligible external magnetic field so that film spots would not be magnetically affected by its presence. Similarly, magnetic fields produced by the resistance type evaporators are quite insignificant. Surrounding the evaporator station devoted to permalloy deposition is a set of circular Helmholtz coils on stainless steel winding forms. These coils are designed to produce a very homogeneous constant magnetic field of about 20 oersteds over a region larger than the total length of the substrate. The latter precaution is necessary because magnetic spots are evaporated one at a time and the first spot to be evaporated is subjected to a 300°C annealing temperature while the second spot is being evaporated. Separate evaporation of the two magnetic film elements was decided upon for two reasons. Firstly, to avoid anisotropy effects associated with non-perpendicular angle of incidence of the evaporated permalloy, and secondly, to permit experimentation with registers having unequal thicknesses of transmitter and receiver elements.

Over the movable substrate carriage are a set of five small "dark" chambers containing photocells for the purpose of measuring film thickness. These chambers contain two ports. A lower port admits a sample of evaporated material from one of the evaporator stations. This material falls on a glass cover slip placed on top of the upper port. An external light source directed from outside the bell jar falls on the upper port. A portion of this incident light passes through the sample of evaporant on the cover slip and reaches the photocell. The amount of light passed in this fashion is a measure of the thickness of the evaporated coating simultaneously being produced on the substrate. This method of measuring film thickness (with photocells internal to the vacuum chamber) is believed to be novel. The light-sensitive elements used for this purpose were cadmium sulfide photo resistors made by Ferroxcube Corp. They are partially encapsulated in glass but there is an exposed surface of epoxy resin material around the base of each photocell. Despite the inclusion of this material in the vacuum chamber no troubles with evacuation or out-gassing were experienced. Similarly, the use of wire in the Helmholtz coils having Formex insulation caused no vacuum difficulties.

D. PRELIMINARY TESTING

Choice of construction techniques for the various evaporator sources required considerable experimentation. Resistance heaters were used in every case but initial designs had too large a crucible size, leading to excessive power requirements and consequent overheating of portions of the surrounding apparatus. Eventually we hit upon the following satisfactory arrangement for the copper and permalloy evaporators. Small crucibles, ¼ inch in diameter and ½ inch long were machined from raw alumina rod-stock and fired. Tightly coiled tungsten heaters were hot-formed to produce a very snug fit around the small crucibles. This heater-crucible combination was placed inside a second, larger alumina crucible (¾ inch by 1 inch) with a glazed interior surface. The outer crucible provided a radiant-energy reflector and baffle that directed a substantial amount of heat back toward the interior heater-crucible combination. Using this type of evaporator source we were able to achieve fast deposition rates of both copper and permalloy with only a little more than 100 watts of heater power. With the very massive construction of our evaporation apparatus no significant amount of over-heating of any surfaces was observed under these conditions.

Evaporation of silicon monoxide presented a different problem. This material vaporizes at a reasonably low temperature, but has a disturbing tendency to "pop-corn." That is, small particles are ejected from the source causing imperfections in the evaporated layer. After some experimentation we settled upon an arrangement in which an alumina crucible of ¾ inch by 1 inch size containing a large quantity of granulated silicon monoxide is heated radiantly from above by a flat spiral tungsten heater. This method worked very well when evaporation rates were kept relatively low. Some preliminary tests of insulation quality of SiO layers between copper layers were made as soon as the evaporator system was in operation.

Peculiar breakdown effects were observed at electric fields of 10 to 20 kilovolts per centimeter which were probably due to pinholes. For voltages of the magnitude we expected in dynamic operation of thin-film devices, however, the SiO layers appeared to be good insulators. Indeed, no difficulties were later experienced with insulation quality when more elaborate thin-film devices were constructed.

E. EVAPORATION SCHEDULE FOR TWO-ELEMENT REGISTER

The following description of a typical evaporation schedule for a two-element register is quite abbreviated, omitting many points which merely reflect good, standard high-vacuum procedures.

A clean glass substrate is placed in the substrate carriage, the system is evacuated, and the several evaporant sources are out-gassed at temperatures near their evaporating temperatures. During this preliminary out-gassing, the substrate carriage is maneuvered to avoid any accidental deposition of material on the substrate. After this operation, system pressure should be about 2×10^{-7} mm of mercury. The substrate is traversed to the first copper station and the lower coupling-loop strap is deposited. Thickness is monitored by the appropriate photocell. The substrate is next traversed to the silicon monoxide station where a layer of insulation is evaporated. Following this, the substrate is moved to the permalloy station and oriented with one spot location directly over the evaporator source. The substrate heater is now energized and a period of 10 minutes is allowed to elapse to bring the substrate temperature into the 300°-to-350°C range. The Helmholtz coils are now turned on and the first permalloy spot is evaporated. The substrate is traversed to a new index position about one inch removed from the first, and the second spot is evaporated. Masking apertures are arranged so that separate photocells may be used to monitor the thickness of each spot. Following the permalloy evaporations the substrate heater is turned off and the substrate is allowed to cool in the presence of the applied magnetic field for about 30 minutes. Subsequently, the Helmholtz coils are turned off, the substrate is brought back to the silicon monoxide station for a second application of insulation, and finally traversed to the second copper station where the top coupling-loop strap is evaporated. During all of these operations the pressure should not rise above about 1 or 2×10^{-6} mm of mercury at the system ionization gauge.

A few other details of the fabrication process are worth mentioning. Permalloy for the magnetic-spot evaporations was initially salvaged from a sample of material that had produced good single magnetic films in a previous experimental activity involving a different vacuum system and a different method of evaporation. Although magnetic material was evaporated at a relatively slow rate (2 to several minutes for a 1000Å film) in our newer system we have reason to believe that melt composition changed over a period of several evaporations. Later runs were made with permalloy sources produced by melting down 83% - 17% mixtures of spectroscopically pure nickel and iron powders. Some anomalous effects were also noted in making thickness measurements with the internal photocells. Use of a mercury arc light source instead of an incandescent lamp helped a great deal in obtaining reproducible calibrations on thickness but it was still necessary to turn off the evaporation source to obtain an accurate thickness reading. The last effect is due to stray light that finds its way from the incandescent evaporator coil to the photocell.

V ELECTRICAL MEASUREMENTS

A. PULSED FIELD EQUIPMENT

All of our experimental measurements on coupled film devices were carried out in a field-free environment provided by a set of 20-inch Helmholtz coils shown in Fig. 11. At the center of this coil-cube, and in a substantial volume of space about the center, earth's field can be nullified to an accuracy of about 0.01 oersted. A Hewlett-Packard clip-on dc milliammeter with the jaws propped open serves as a convenient gauss-meter for carrying out the nulling operation. Three regulated current supplies furnish the independently adjustable currents for the three orthogonal Helmholtz coil windings. At the center of the Helmholtz cube is a set of adjustable lucite fixtures which hold the thin-film register and support the drive, bias and clear windings (see Fig. 12). These windings form two orthogonal sets which can apply fairly homogeneous magnetic fields to either film element in the easy or transverse axis directions. Each winding consists of 10 turns of Number 32 wire and presents an inductance of about 1.3 microhenry to the current drivers. Field calibration data for these coils is 6.5 oersteds per ampere for the innermost drive and bias windings and 4.9 oersted per ampere for the outer clear windings. Both sets of coils may be adjusted independently for angular position.

Three types of current driver pulse sources were used in the switching experiments. A multi-channel laboratory pulse generator using hard-tubes in the output circuits provided a programmed chain of pulses adjustable in amplitude from zero to a few amperes and with rise and fall times of about 200 nanoseconds. A second set of pulsers manufactured by Digital Equipment Corp. provided similar current pulses with rise and fall times of about 100 nanoseconds. For experiments requiring faster pulsed fields, two extra pulse channels were constructed in which a 2D21 thyratron discharged a coaxial cable. This pulse source shown schematically in Fig. 13 produced pulses of up to 6 amperes with rise and fall times of about 20 nanoseconds, limited by the inductance of the driven windings.

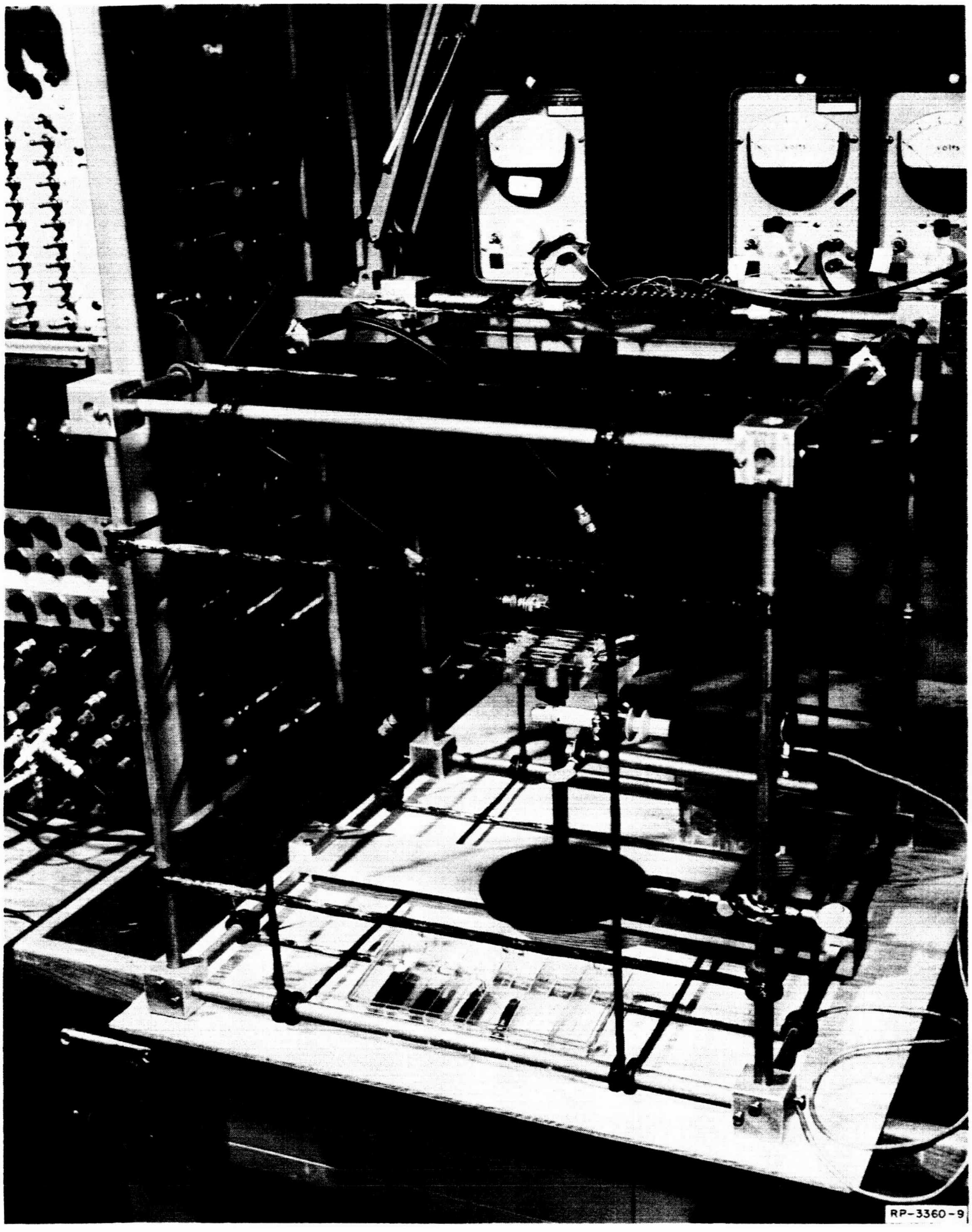


FIG. 11 ELECTRICAL TEST APPARATUS

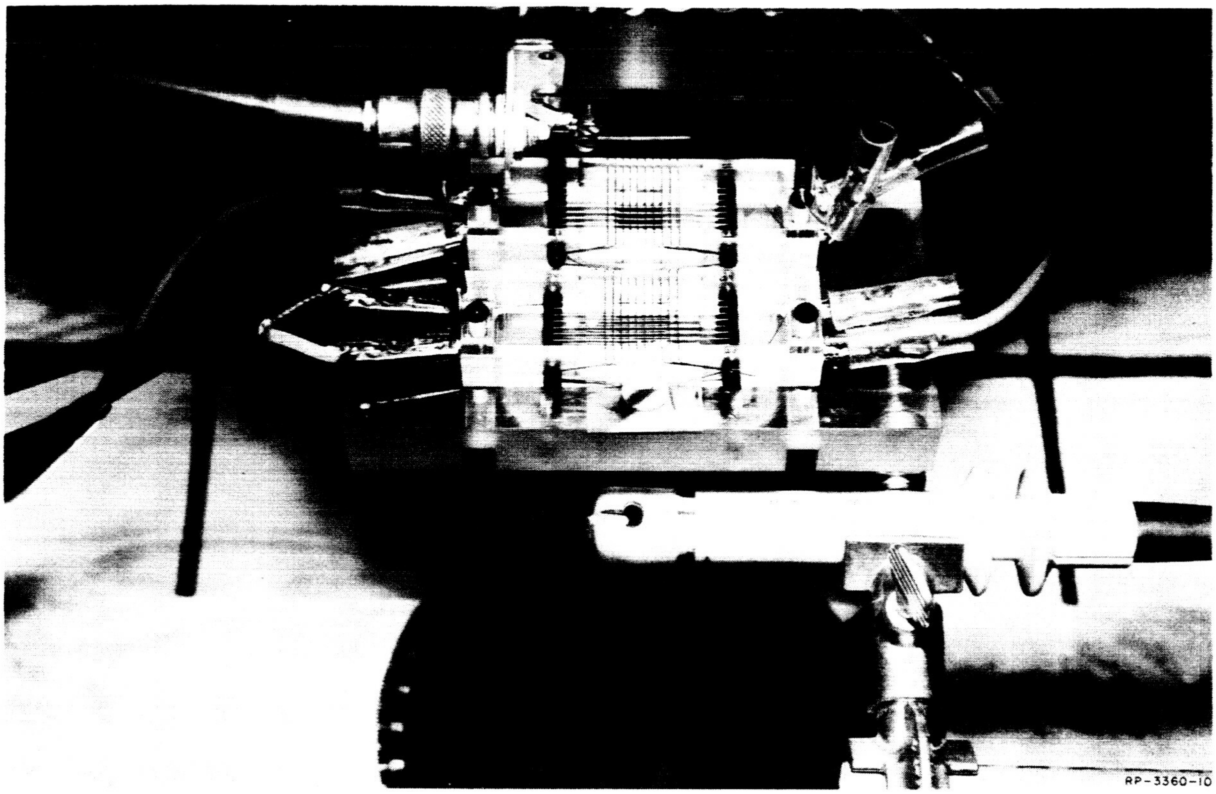


FIG. 12 THIN-FILM REGISTER SUPPORT FIXTURE SHOWING DRIVE, BIAS AND CLEAR WINDINGS

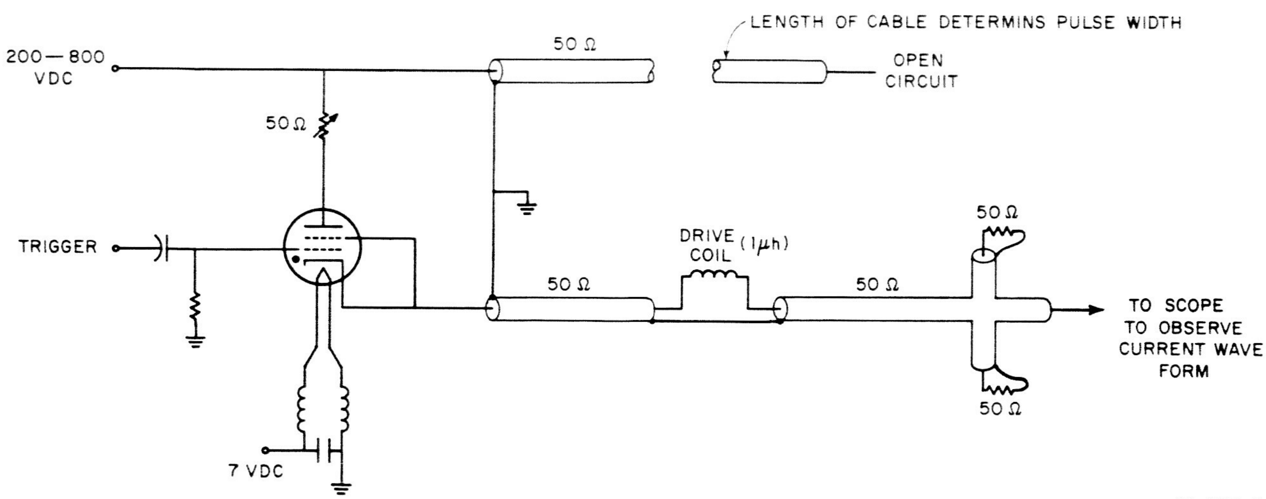


FIG. 13 HIGH-CURRENT/HIGH-SPEED PULSE SOURCE SCHEMATIC DIAGRAM

Output voltages produced by the thin-film elements during switching are sensed by a transistor wide-band differential preamplifier. Connection to the preamplifier is made by a very thin twisted lead-pair which is attached directly to the mid-point of the evaporated coupling loop. The method of attachment is shown in Fig. 8.

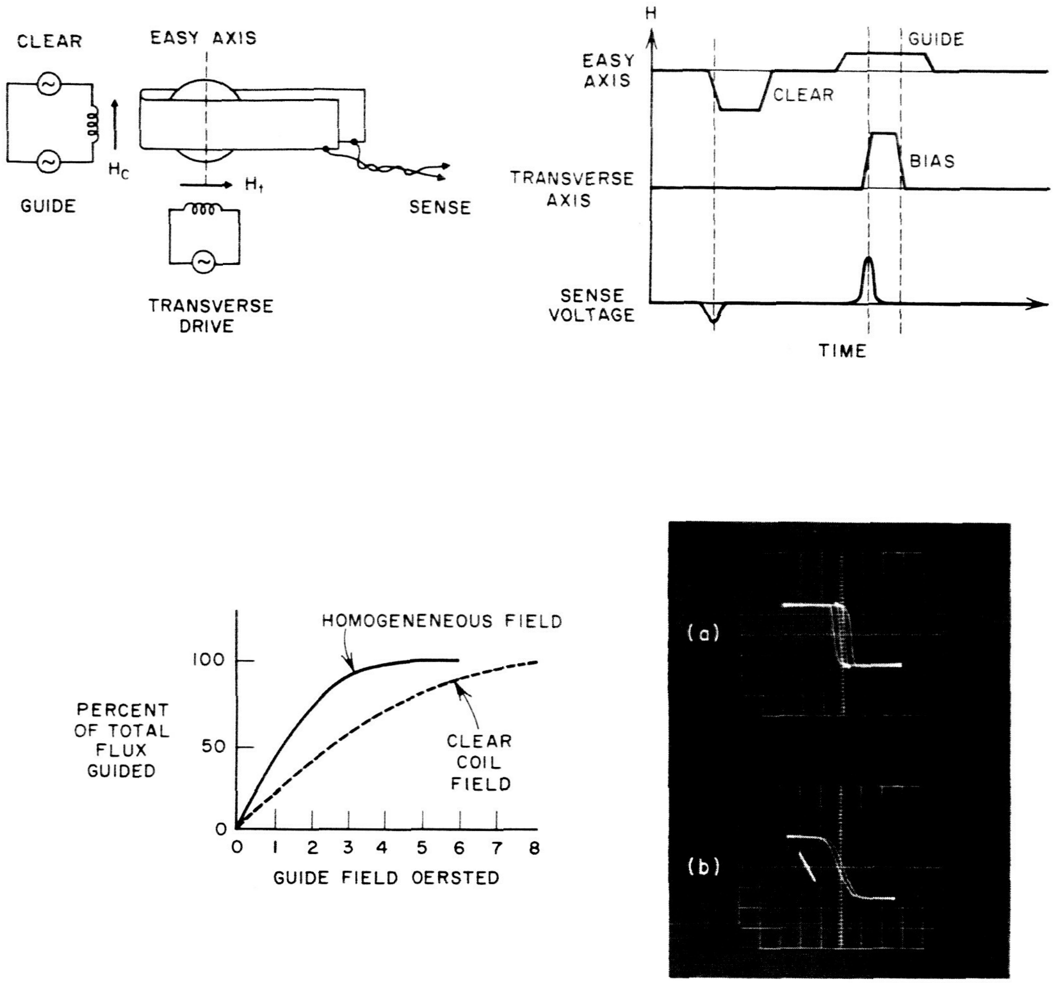
B. EXPERIMENTAL RESULTS

1. SINGLE FILM SPOT WITH EVAPORATED COUPLING LOOP

Before proceeding with the construction of two-element registers we made a sample register having only one magnetic-film spot situated in a coupling loop with one end open-circuited. In other respects this device was dimensionally similar to subsequent two-element registers. The reason for investigating this device was that we wished to make flux switching measurements that would be free from loading effects produced by a second film spot.

The first experiment tried was a measurement of the guided fall-back behavior of the single film element. The experimental set-up is schematically illustrated in Fig. 14. A large clearing field is repeatedly applied to establish the film element in a saturated easy-axis direction. Following the clear field a small guiding field is applied in the opposite easy-axis direction. After the guide field is established a strong transverse field drives the film magnetization to the transverse axis. The transverse field is then relaxed and the small guiding field attempts to return film magnetization to the opposite easy-axis direction (from the clear state). The voltage pulse observed across the coupling loop at clear time is a measure of the total change of flux in the element after one switching cycle. In an ideal transfer M would completely reverse direction and the time-integral of the pulse observed at clear time would be 2ϕ. The voltage pulse that coincides with the trailing edge of the transverse drive pulse measures the amount of flux actually steered by the guiding field during fall-back. Ideally this pulse would have an area equal to ϕ.

A graph of guided flux versus guiding field is shown in Fig. 14 for two different methods of applying the guiding field. The graph marked "homogeneous field" represents the case where guiding field was produced by a set of Helmholtz coils 10 cm in diameter located around the film spot.



(a) EASY AXIS HYSTERESIS LOOP
(b) TRANSVERSE AXIS HYSTERESIS LOOP

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FIG. 14 SINGLE-ELEMENT GUIDED FALL-BACK EXPERIMENT TYPE 1

In this case the guiding field was known to be very uniform. The graph marked "clear-coil field" was obtained when guiding field was applied by one of the small clear windings visible as the outer set of conductors in Fig. 12. In the latter case the field is not very uniform over a volume as large as the film spot. In the homogeneous field case it can be seen that a guiding field of about 0.5 oersted produced essentially complete switching of the film element. In the non-uniform field situation, nearly double this amount of guiding field was required as measured at the center of the element.

A pair of hysteresis loops for the single-element register is shown in Fig. 14. It can be seen that the transverse loop is rather poorer than one might hope for. This particular film spot was, however, about 5000Å thick which could account for the non-ideal transverse loop. Nevertheless the rotational behavior observed under homogeneous field conditions was not bad. The H_k value taken from the hysteresis loop measurements is 5 oersteds so that guiding was essentially perfect for a field of 10 percent of H_k. This corresponds to one of the static equilibrium trajectories illustrated in Fig. 3. It indicates that complete coherent rotation is preserved to an angle of 58° away from the easy axis. According to the theoretical analysis in Sec. III this rotational behavior would probably not be good enough to effect a lossless transfer between two film elements.

A second experiment of the guided fall-back type was undertaken to determine how the film spot would respond to a guiding field applied by the coupling loop itself. This is the situation that would have to work satisfactorily in a two-element register where guiding field is produced by a voltage pulse at the transmitter element driving current into the coupling loop. The experimental set-up is schematically illustrated in Fig. 15. Again, the film element is repeatedly cleared to establish a definite reference state. A transverse bias is applied following the last clearing pulse. Coincident with the trailing edge of the transverse bias pulse a fast (0.15 μs) pulse of guiding current is applied directly to the coupling loop straps. This current pulse is meant to simulate the current that would flow from a transmitter element switched at a similar speed. The photograph in Fig. 15 shows a composite series of waveforms observed for one particular value of guiding field applied in two different easy-axis directions. The upper traces show the transverse bias field and the two different polarities of guiding field applied just as the transverse pulse is decaying toward zero. The lower traces represent the voltages observed at the coupling loop under the following four conditions listed in order of amplitude from largest to smallest:

(1) Positive guiding field
(2) No guiding field
(3) Negative guiding field
(4) No transverse bias.

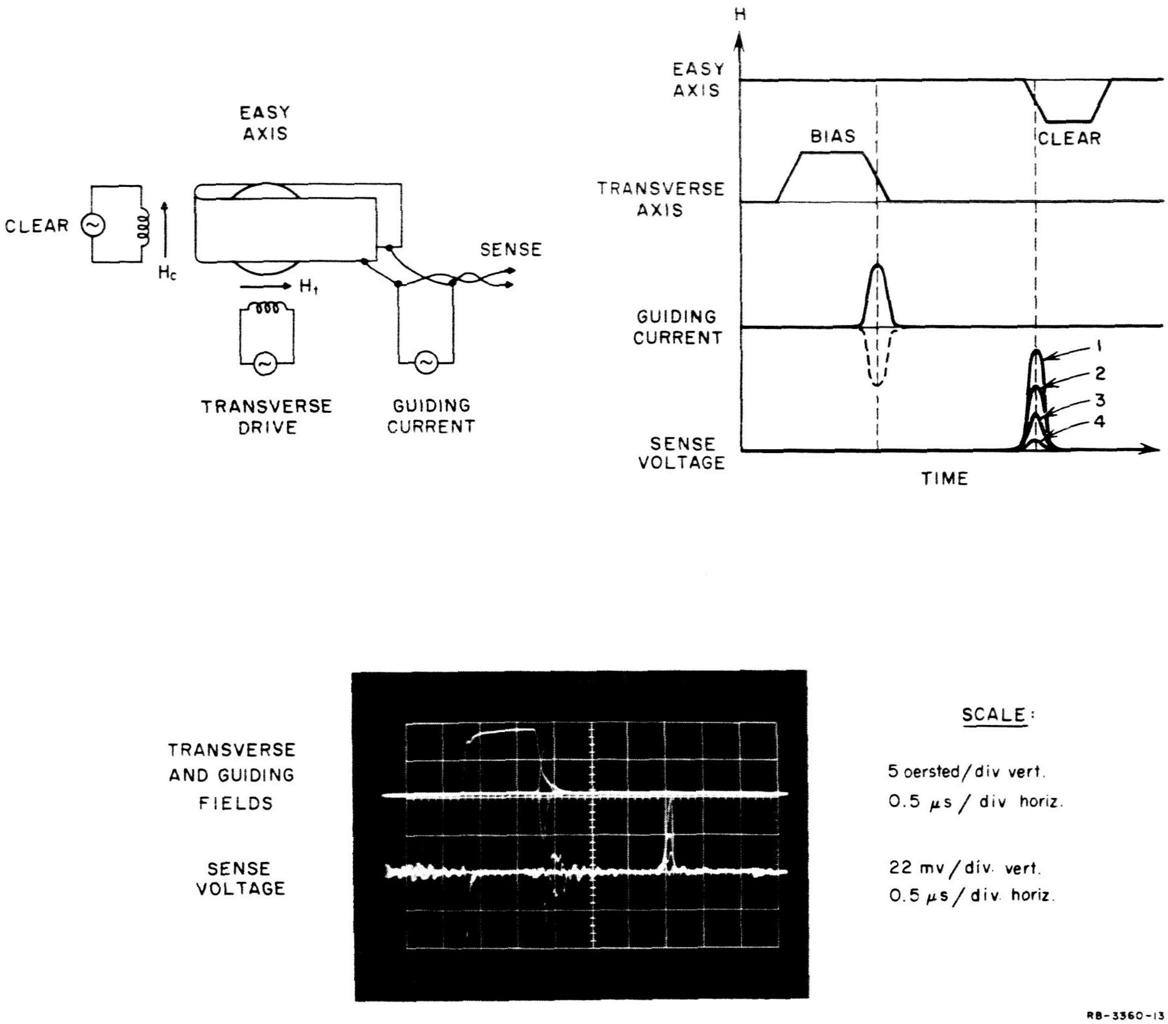


FIG. 15 SINGLE-ELEMENT GUIDED FALL-BACK EXPERIMENT TYPE 2

The significant waveforms are the narrow pulses in the lower right of the photograph. Other signals on the sense winding are meaningless noise and ringing due to applied drive and guide currents. The voltages at the sense leads of the coupling loop during clear time measure the amount of flux guided toward one of the easy-axis directions. The largest sense pulse represents a complete reversal of the film magnetization. Its area is 2ϕ. The pulse rising to exactly half this amplitude occurred when no guiding field was applied. Thus the film magnetization did not return to either easy-axis direction and the film broke up into domains. The subsequent clear pulse consequently switched only an amount of flux ϕ in re-establishing the easy-axis magnetization condition. Trace (3) in Fig. 15 represents the condition in which the film magnetization should have all returned to the original easy-axis direction. From the size of the voltage pulse seen at clear time one can infer that the guiding was not complete in the case illustrated since no switching voltage should occur during clearing if return to the original easy axis was complete. The final voltage pulse (or lack of it) was merely included to show the amount of noise voltage induced in the coupling loop by the clear pulse. No actual flux change other than a very small amount of elastic switching in the film element occurred at this time because no transverse bias was previously applied.

By means of experiments of this type we were able to estimate the amount of guiding field and guiding current required to successfully steer the receiver element. For the single film device tested these figures came out to be quite close to the guiding field strengths measured with the *inhomogeneous* field produced by the clear coil and illustrated as the dotted graph in Fig. 14. A tentative conclusion from this data is that the field produced by the coupling loop is not sufficiently uniform and that a wider coupling-loop strap covering all of the film element would be more desirable. Another possible explanation is that the film spot was a reasonably good coherent "rotator" only at low switching speeds. When higher-speed guiding pulses were applied the rotational behavior began to deteriorate. In any event, the peak guiding current required to completely steer the element was about 0.75 ampere in the coupling loop. This current could easily be produced by fast switching of a transmitter element of similar thickness working into a short-circuited coupling loop. As pointed out in Sec. III, however, receiver voltage seriously limits current flow from a transmitter element so that it is doubtful whether the film element measured could have been successfully switched by an identical transmitter element.

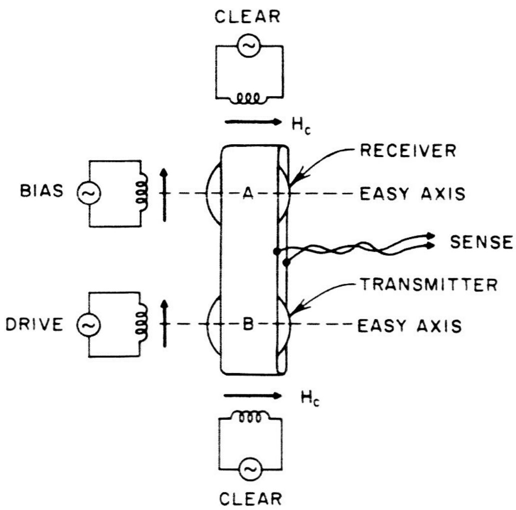
2. Coupled Film Pairs

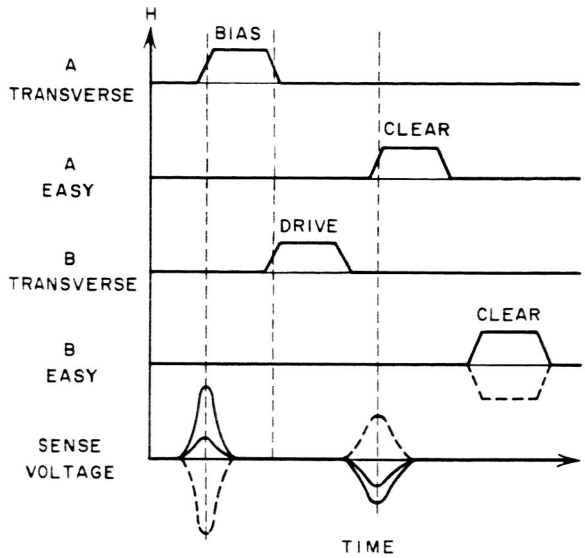
As soon as we began to make registers with two magnetic film elements we began to experience great difficulty in securing good magnetic properties in both evaporated spots. The physical appearance of our thin-film devices was excellent. The silicon monoxide insulation and copper coupling-loop structures seemed very satisfactory, but the magnetic elements were very poor. A series of eight consecutive two-element registers was constructed with minor procedural variations. Occasionally one spot would have fair magnetic behavior while the other spot was usually worthless. Variations in substrate temperature, insulation thickness, melt composition, evaporation rate and out-gassing procedure were all tried without significant success. Finally, when project time was entirely exhausted we discovered what may be the explanation for the erratic properties of our magnetic films. In carefully inspecting empty alumina crucibles that had contained permalloy for evaporations we noticed some signs of erosion of the alumina material. This deterioration of the alumina (which did not occur at the copper evaporators) is probably due to electrolysis of the alumina by the resistance heater. The effect does not seem to occur when radio frequency heating of the evaporator is employed. This unsuspected effect very probably contaminated our permalloy sample with aluminum which reached the substrate in unknown proportions because of its low vapor pressure.

Electrical measurements were performed on all of these registers and attempts to transfer flux by guided fall-back were made on several. When one of the magnetic spots was clearly bad the register was cut in two so that independent guided fall-back data could be obtained on the better element by procedures explained in Sec. V-B-1 above. These measurements were interesting, but did not contribute much toward establishing feasibility of the proposed transfer process. What they did reveal was that our magnetic spots had widely varying coercive fields (5 to 50 oersted) mostly higher than 10 oersted, poor rotational behavior, and occasionally low remanent flux. A number of different pulse tests were devised to measure these magnetic effects but the particular measurements do not seem sufficiently important to report separately.

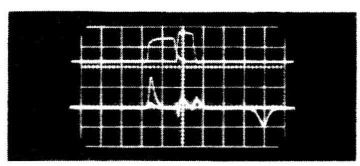
The closest approach to a successful flux transfer was achieved with register No. 6. This register had two spots with quite similar behavior. Film thickness was about 1000Å. For both films H_k was about 5 oersted although it was difficult to measure because rotational switching was poor, as can be seen from the transverse hysteresis loops shown in Fig. 16. The experimental apparatus is also illustrated schematically in Fig. 16 together with the pulse regime and some of the observed waveforms.

Again, two types of experiment were performed which give independent indications of the effectiveness of the guided fall-back process. The

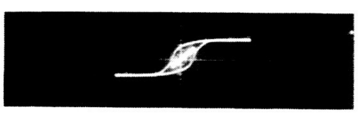




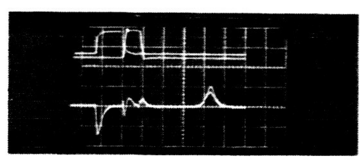
(a)



EXPERIMENT I



(b)



EXPERIMENT II

(a) EASY AXIS HYSTERESIS LOOP
(b) TRANSVERSE AXIS HYSTERESIS LOOP

SCALE: 5 oersted/div

SCALE: HORIZ. 0.5 μs/div
VERT. 60mv/div

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FIG. 16 GUIDED FALL-BACK FLUX TRANSFER IN A TWO-ELEMENT REGISTER important voltages observed at the sense amplifier are indicated in the line drawing. Other signals appearing on the lower traces of the accompanying photographs in Fig. 16 are irrelevant noise signals produced by drive and bias pulses. In Experiment I the transmitter B is repeatedly driven in the transverse direction while the bias current at the receiver A is relaxed. The transmitter's initial easy axis direction is occasionally changed, however, by reversing the direction of its clear pulse. The receiver element is not cleared at any time. At the leading edge of the transverse pulse applied to the receiver a voltage is observed corresponding to the flux steered by the transmitter during the *preceding* switching cycle.

Experiment II is similar except that the receiver is cleared after each flux transfer. At receiver clear time a voltage pulse is observed at the sense winding corresponding to the residual *unswitched* flux component in the direction of the receiver clear pulse. Thus, if flux transfer were perfect, one direction of receiver clear would produce no voltage while the other direction would produce a voltage-time integral of 2ϕ.

The photograph labeled Experiment I actually is a superposition (for contrast) of Experiment I and Experiment II for similar clear directions at transmitter and receiver. The small pulse in the positive direction at the left hand side of the sense-trace is the flux switched at the receiver by the transmitter during drive. The larger pulse at the same time, and the subsequent negative pulse, represent the same set of conditions except that the receiver element was cleared. Thus, the first large pulse is the receiver flux ϕ while the second negative pulse is the unswitched residual flux after a transfer.

The photograph labeled Experiment II is also a superposition of two traces corresponding to different directions of transmitter clear pulse but similar directions of receiver clear pulse. The significant waveforms are the two coincident pulses occurring on the right hand end of the sense-trace. If a complete transfer of flux from the transmitter to the receiver element had occurred, one of these pulses would have had an area of 2ϕ. The other should have been zero. The difference in area between these two pulses is a measure of the amount of flux actually steered by the transmitter element. This measurement is more accurate than Experiment I in revealing the percentage of receiver flux actually switched because noise and amplifier non-linearity are more nearly compensated. Integration of such pulses showed that under the best switching regime we could obtain, a maximum guided fall-back flux transfer of 28% of the receiver flux could be secured.

As expected from previous theoretical considerations, the flux transfer was extremely sensitive to drive and bias pulse timing. Especially under fast-pulse conditions a variation of 2 or 3 nanoseconds in phase relationship between bias and drive encompassed the whole apparent range of significant receiver steering. It is interesting to note that the observed maximum value of switched flux at the receiver (28%) would correspond to an angular displacement of receiver magnetization of 16° if *no* domain formation occurred. A good magnetic film could have reached the easy axis "under its own steam" from this angular position.

VI SUMMARY AND CONCLUSIONS

The research program just concluded had three phases with separate degrees of success. In the theoretical phase we examined the expected behavior of coupled magnetic elements and found that even under relatively idealized conditions the guided fall-back mode of flux transfer would depend for success upon the eventual production of systems with magnetic elements having very good rotational behavior and relatively low coercive fields. The necessity for very accurate timing of clock-pulse sources was also deduced and subsequently verified by experiment. It could not, however, be concluded that the proposed system was impractical because single thin-magnetic-film elements had previously been produced that seemed to satisfy (just barely) the system requirements.

The phase in which we designed and constructed our evaporation equipment consumed somewhat more time than we could comfortably afford. We are satisfied with our choice of fabrication procedures and feel that a useful and flexible piece of apparatus for subsequent magnetic-film investigations has been produced. Nevertheless, some technical problems did arise in the use of this evaporation system that were not satisfactorily disposed of before conclusion of the project interval. In particular, the completely unexpected inability to obtain consistently good magnetic films hurt the program of electrical experimentation severely.

In the area of electrical testing of thin-film registers we were only partially successful. It was demonstrated that thin evaporated transmission lines of the type used for coupling loops behave almost exactly as expected from theoretical calculations. Guided fall-back by currents sent through such structures was repeatedly achieved under conditions that might have been produced by switching a good transmitter element. Partial switching of a receiver element by a transmitter element was also observed; however, the flux transmitted (28 percent of the total available) was not sufficient to satisfy flux gain requirements. Reasons for the failure can be identified with the poor rotational behavior of the magnetic films we were able to produce. Our tentative explanation of this fact is that the permalloy source was occasionally contaminated with aluminum reduced from the crucibles employed.

A partially intuitive conclusion based on experience gained during this project is as follows: Thin film registers of the type we visualized could, with considerable additional effort, probably be made to operate. The potentialities of this method as a practical high-speed logic system, however, now appear rather dim. The difficulty of obtaining a simple positive transfer of information from one element to another would be considerably aggravated by the necessity to fan-out to a multiplicity of receiver elements. It can be shown on purely theoretical ground that this is quite difficult, and experimental results support this conclusion. In the face of competition from a number of other high-speed logic systems it would seem that this method of utilizing thin-magnetic-film properties may not survive.

ACKNOWLEDGMENT

D. C. Engelbart conceived the thin-magnetic-film logic system explored in this report and developed system concepts including the guided fall-back mode of operation.

V. W. Hesterman designed much of the experimental equipment and made all of the physical and electrical measurements on thin-magnetic-film devices. His ingenuity and collaboration are greatly appreciated.

V. C. Sanford did the mechanical design work involved in the construction of our vacuum apparatus for thin-film evaporations.

We are indebted to Floyd Humphrey of J.P.L. for many helpful discussions during the course of the project.

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